



Presentation of a New Sensor Enabling Reliable Real Time Foot Plantar Pressure Distribution Retrieval

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Abstract. Monitoring plantar load conditions becomes useful in many health care fields, e.g. podiatric and orthopedic applications, rehabilitation tools, sports and fitness training tools, and in-field diagnosis and prevention tools for posture, balance, loading and contact times monitoring. IEE target is to provide a single insole-solution for daily usage in order to acquire information on the plantar load distribution for health prophylaxis in a large range of different shoe configurations. In this paper, we introduce for the first time a new **High-Dynamic (HD)** multi-cell smart insole sensor enabling advanced real-time foot plantar pressure monitoring applications. The in-situ measurement of the dynamic plantar load distribution provides an important new source of information that can be combined with traditional monitoring systems often based on accelerometer and gyroscope sensors. In fact, the new smart insole as presented here, facilitates the discovery in an early phase of any biomechanical mismatch in the walking or running gait of its user. Specific datasets have been recorded from a representative healthy population with different monitoring tools, i.e. force plate, pressure matrix and our new smart insole. The aim was to study the similarity of measurements recorded by each system on a defined measurement protocol. It is shown that the new monitoring device provides a competitive methodology to measure static and dynamic foot plantar pressure distribution. The system flexibility and robustness enable the development of new real-time applications, such as high peak pressure detection for diabetics, activity tracking, etc. The paper is organized as follows: we provide in Sect. 1 an overview of challenges and opportunities around foot pressure monitoring and discuss the sensing capabilities. Then we give a description of the new smart insole designed by IEE in Sect. 2. Next we define in Sect. 3 the measurement protocol based on 3 different systems, followed in Sect. 4 by a comparison of their efficiency and reliability. Finally, Sect. 5 provides related works and Sect. 6 concludes the paper.

Keywords: Foot pressure distribution · Smart insole · Force plate

1 Introduction and Motivation

IEE's smart insole provides users with in-field dynamic monitoring capabilities of the foot plantar pressure distribution. It covers a wide measurement range of pressure and can thus be applied to walking, running, and jumping activities. Connected to a wearable electronic module, it provides real-time data about the plantar contact pressure from proprietary-designed robust high dynamic pressure sensing cells. Each insole is composed by a discrete number of sensor cells, which supports an easy electronic sensor readout and a high measurement frequency. According to an easy integration, it can support foot practitioners in real-life correction diagnosis. The foot pressure map is actually needed in order to identify special gait patterns and design optimized shoes adapted to each person, so that pain and injury risks can be reduced during physical activities thanks to a dedicated training control. This information can also be retrieved with large fixed pressure detection plates that measure on-line the contact pressure between barefoot and the ground under lab condition. Our new thin sensor belongs to a second type of mobile insole-system solutions. It does not affect the overall shoe comfort felt by the user during daily activities due to its high flexibility and robustness. An **Electronic Control Unit (ECU)**, connected to the sensor, manages data communication to third-party interface systems such as smart-phone, tablet or laptop where additional processing can be applied. This allows mobile real-time applications, that are not feasible with uncomfortable monitoring equipments such as force plates, due to large electronic devices, connectors, cabling etc.

2 Sensor Description

The smart insole is based on a flexible, foil-type sensing device. It detects sole force loads by providing locally in real-time transient dynamic electrical signals. As a consequence, pressure, strain and dynamic force load can be simultaneously monitored. The smart insole is composed by eight individual cells spatially distributed in the main areas where foot pressure changes statistically occurs, i.e. two cells for the heel, one cell for the mid-foot, three cells for the metatarsal area and finally two cells for the toes (see Fig.1). Each sensor cell covers a

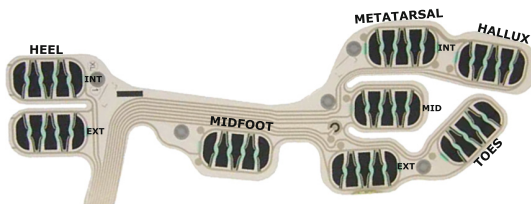


Fig. 1. IEE's smart insole comprising 8-HD pressure cells. The cell design has been elaborated within a comprehensive IEE research project [1,2].

detection area of about $30 \times 15 \text{ mm}^2$ in order to be robust against lateral shifts of the plantar pressure loads that can be due to individual anatomic deviations and relative movements of the foot inside the shoe. The new **HD Force-Sensing Resistor (HD-FSR)** multi-cell smart insole sensor enables advanced real-time gait analysis applications. HD-FSR sensors, with their individual triangular cell segmentation, cover a wide pressure range from 250 mbar up to 7 bar. Their robustness enables up to one million actuations under highest humidity conditions. Lifetime variation is smaller than 15%.

3 Measurement Protocol

The goal of the proposed measurement protocol is to show the reliability and repeatability of our sensor in static and dynamic configurations. A calibration process is firstly performed in order to build a unique mapping between each cell response and the applied pressure. An homogeneous pressure from 0 to 6 bar is applied on the complete insole by means of a specific membrane tester system. Then a look up table is generated and links uniquely each sensor **Analog to Digital Conversion (ADC)** value to the applied pressure. A spline interpolation model is finally computed in order to convert any ADC value measured by a cell into its pressure load. This calibration process has been applied within IEE's laboratories for each insole in order to provide the same response level to all sensor cells. Each insole has been connected to a Kinematix- ECU enabling data recording at 100 Hz, combined with a 3D accelerometer and gyroscope [3]. Data have been wirelessly exchanged by means of a Bluetooth communication between ECU and a computer.

In order to study the sensor reliability, an alternative monitoring system [5] designed by Lion-Systems S.A. and based on a force plate, has been tested (see Fig. 2). It consists of a walkway of 3.2 m, composed by four blocks ($L80 \times W60 \times H6 \text{ cm}$). One block includes a force plate from Kistler Instruments that records the ground reaction force exerted by the foot during gait. Four cameras recording 656×490 pixel images at a frame rate of 140 Hz are placed on each corner of the force plate with four metallic arms. Data from the cameras (motion capture based on 3D-coordinates of colored markers located on foot and leg) and force plate are simultaneously recorded. We also used a pressure platform WIN-POD ($L53 \times W60 \times H4.5 \text{ cm}$) from the French company Medicapteurs [4] in order to retrieve the spatial pressure distribution over time. WIN-POD uses an IEE sensor mat which enables podometry data analysis according to its high sensitivity, its wide dynamic range of measurements, its precision and homogeneity at a frequency rate of 200 Hz. The active surface is about $400 \times 400 \text{ mm}^2$, composed by 2304 individual calibrated resistive cells (48×48 matrix of individual cells of size $8 \times 8 \text{ mm}^2$). The pressure range covers 0.4 N to 100 N.

For this study, five pairs of insoles M (EU-38 for women) and three pairs XL (EU-44 for men) have been used. Twenty three subjects had participated to a predefined measurement protocol for static (standing) and dynamic (walking) activities. The aim of the study was to check the accuracy of the new sensor in

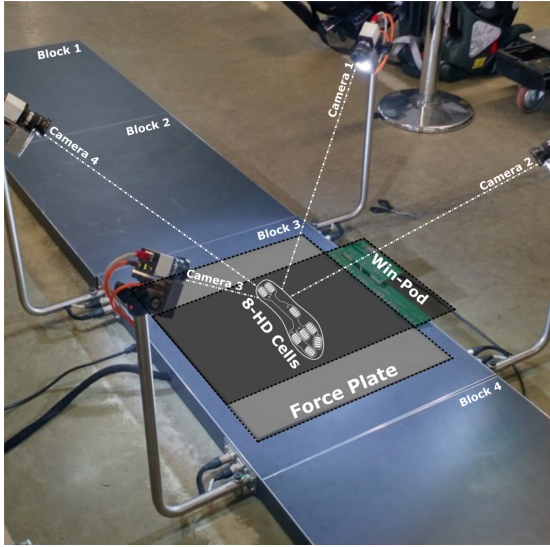


Fig. 2. Measurement set up environment. Three measurement systems (Force Plate, WINPOD and IEE’s Smart Insole) have been synchronized in order to record at the same time pressure information of a complete gait cycle.

comparison to more complex systems often used as a reference in gait analysis to monitor plantar pressure distribution under lab conditions. For the static condition, test persons had to keep their neutral position without moving during ten seconds. Users had been also asked to wear flat shoes which can be expected to provide similar plantar load conditions as the barefoot one because any sole effect can be neglected. For the dynamic condition, test persons had been asked to walk at their natural speed on the four blocks. The starting distance from the force plate had been adapted for each person in order to record a specific step without gait modification. Test persons started in a stationary position. Afterwards, they walked forward a few meters with natural pace. Proper time synchronization allows a direct comparison of the pressure signal of the corresponding step reaching the force plate and the data extracted from the smart insole. Each test was composed by three trials in order to study the sensor repeatability.

4 Results

The standard force curve for walking is typically composed by a first peak corresponding to the breaking phase, a drop linked to the support phase and a second peak for the propulsion. If the user touches the ground with a high force, an additional high pressure peak at the heel appears very early during the gait cycle. The peak corresponding to the breaking phase occurs when the pressure is distributed between Heel and Mid-Foot. The force drop can disappear between the breaking and propulsion phases in case of a comparatively large plantar

mid-foot surface, for instance for flat feet. For people with a distinct pronounced arch, the drop is more important.

The vertical force measured by the force plate had been correlated with the plantar pressure distribution recorded with the 8-HD sensor cells for each step trial. Both measurements were done simultaneously on the same step. Data had been normalized with the body weight for the force plate, and the sum of all cell responses for the insole, both under static condition. A typical pressure profile obtained with the insole sensor and the corresponding individual cell responses are plotted in Fig. 3(a).

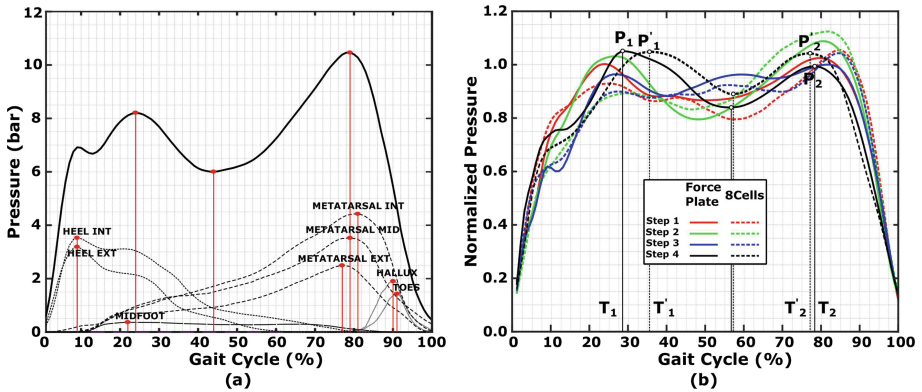


Fig. 3. (a) Typical pressure profile recorded with the new smart insole sensor. (b) Similarity between walking profiles recorded with the insole and the force plate. (Color figure online)

Figure 3(b) compares four steps measured with the insole and the force plate, randomly selected from the global dataset. For each step, the normalized pressure for the complete gait cycle has been plotted as solid (dashed) line for the force plate (insole, respectively). The step duration has been also normalized in order to enable a direct comparison between each walking profile. We can observe a high similarity in the dynamics. For instance, if we consider Step 4 in Fig. 3(b), signals from each system follows the same trends. T_1/T_2 corresponds to the relative timing with respect to the gait cycle duration when the first/second pressure peak occurs of relative amplitude P_1/P_2 . The first peak practically occurs at around 25% of the gait cycle. A minimum is reached most of the time at around 60% and the second peak at around 80% of the gait cycle. A similarity metric $S(\delta)$ has been defined as the gait cycle proportion where the ratio between the force plate and 8-HD sensor cells belongs to the range $[1 - \delta, 1 + \delta]$ as can be used to quantify the similarity between the two systems' measurements. If we used an accepted deviation rate of $\delta = 0.2$, a relative difference of 20% is allowed between the two sensors for each time index. The obtained results for S are plotted in Fig. 4 for each step and subject weight. The metric intrinsically

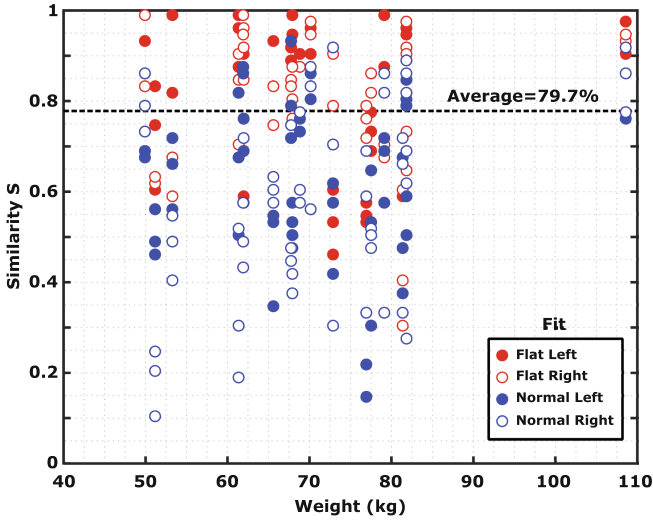


Fig. 4. Similarity metric S comparing force plate vs. insole for the complete dataset plotted versus subject weight. The force plate and the smart insole present similar signals when S is close to 1. (Color figure online)

belongs to $[0, 1]$. $S = 0$ if the difference between the two signals is always greater than 20% during the complete gait cycle. S reaches an average value of 79.7% for the overall experiment. Moreover, S is larger for flat shoes (red symbols) in comparison to normal shoes (blue symbols). This is due to the sole effect mentioned earlier which aims to distribute the pressure over the complete shoe. Thus the data acquisition inside the shoe gives additional information compared with force plate measurements and allow to study the influence and potential differences between different shoe types. As a conclusion, the new insole sensor provides very similar results as the force plate when measuring the total force load.

5 Related Works

Various complex systems have been released on the market enabling detailed gait analysis. They are mainly based on image processing by means of expensive data acquisition systems that need large laboratory environment, floor sensors, and wearables carried directly by the test persons. Researchers often rely on floor sensors, such as so-called sensor matrices or baropodometric mats since they provide a complete overview in real time of the pressure distribution below each patient’s foot. Another interesting type of monitoring system comprises force plate sensors. In that case, the main issue is the large set up environment and also the impossibility to monitor the users’ gait during their daily activities. Cheap wearables enable to measure different characteristics of the human gait

based on pressure sensors directly placed on the patient's insoles and also inertial sensors that are the most widely used monitoring system in gait analysis. Gait data recorded in real conditions outside a laboratory, and also on the long term, become more relevant for an accurate analysis. The main advantage of these systems is that users can wear them in their daily life. Following pre-defined measurement protocols e.g. in case of force plate application is often felt as a heavy constraint by users. This has also an deep impact on data as the recorded gait signals can differ from the natural ones. In fact patients unconscious adapt their gait in order to walk on the right position where the sensor is located. These changes affect the measurement repeatability.

In [6], Herran et al. presented a complete survey on available systems focusing on gait analysis. They referenced a non-exhaustive list of sensors covering a large range of method, application, accuracy, price and ease of use. Force plates and wearables remain the most used candidates. For instance, in [7], Hadopp et al. presented a smart-shoe composed by three pressure sensors mounted on a flexible insole. It can reliably differentiate the most common postures and activities, according to an additional three-axis accelerometer. In [8], Sanghan et al. used the Pedar-x system, composed by an array of 99 capacitive sensors placed on a 2.6 mm thick insole. Da Rocha et al. selected in [9] the pressure mapping system Matscan from Tekscan Inc. In [10], Wafai et al. monitored the dynamic plantar pressure distribution in respect the F-scan in-shoe pressure measurement system composed by 960 sensors from Tekscan. In [11], Ferber et al. presented their smart shoe. They concluded that the pressure recorded by their device is highly correlated with data monitored simultaneously with a gold standard pressure-sensing device.

6 Conclusion and Outlook

In this paper, we introduced a novel smart insole sensor which consists of a flexible carrier foil comprising eight individual pressure cells. This system enables advanced real-time foot plantar pressure monitoring applications. It offers a new research tool in order to monitor in a reliable and accurate way the gait dynamic of its user. We have studied the correlation between the data recorded with the new smart insole, a force plate and a pressure matrix based on a defined measurement protocol. It could be shown that this new sensor device provides in fact a competitive approach to measure static foot plantar distribution and also gate dynamics in daily life. Future works will consist of the design of enhanced algorithms in order to automatically extract gait features. A potential next goal can be the characterization and the classification of individual walking profiles into healthy and non-healthy categories. Warning notifications can be provided in case of walking profile anomalies that can be caused by an illness evolution. For that, sophisticated mathematical models will be used to generate the complete pressure distribution on each foot based on spatial interpolation schemes.

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